

Use of corn distillers' dried grains to reduce enteric methane loss from beef cattle

S. M. McGinn¹, Y.-H. Chung¹, K. A. Beauchemin¹, A. D. Iwaasa², and C. Grainger³

¹Agriculture and Agri-Food Canada, Lethbridge, Alberta, Canada T1J 4B1 (e-mail: sean.mcginn@agr.gc.ca);

²Agriculture and Agri-Food Canada, Swift Current, Saskatchewan, Canada S9H 3X2; and ³Department of Primary Industries, Ellinbank, Victoria 3821, Australia. Received 29 December 2008, accepted 26 March 2009.

McGinn, S. M., Chung, Y.-H., Beauchemin, K. A., Iwaasa, A. D. and Grainger, C. 2009. **Use of corn distillers' dried grains to reduce enteric methane loss from beef cattle.** *Can. J. Anim. Sci.* **89**: 409–413. There are significant emissions of greenhouse gases (GHG) from agriculture, and a major source is enteric methane (CH₄) from ruminants. Our study reports the impact on enteric CH₄ emissions when barley grain (35% of the dietary dry matter (DM) was replaced by corn distillers' dried grains with solubles (DDGS, adding 30 g fat kg⁻¹ dietary DM) in the backgrounding diet of growing beef cattle. The addition of DDGS reduced CH₄ emissions (g d⁻¹) by 19.9%, and by 16.4% when adjusted for DM intake [g (DM intake)⁻¹] or by 23.9% when adjusted for gross energy (GE) intake (% of GE intake). Adding DDGS to cattle diets reduced CH₄ emissions, but the effects of higher N content of the manure on emissions of nitrous oxide and ammonia need to be accounted for to complete the evaluation of the environmental impact of feeding DDGS to feedlot cattle.

Key words: Methane, beef cattle, corn distillers' dried grains with solubles, lipid, greenhouse gas emissions, sulphur hexafluoride

McGinn, S. M., Chung, Y.-H., Beauchemin, K. A., Iwaasa, A. D. et Grainger, C. 2009. **Utilisation de drèches sèches de distillerie de maïs pour réduire les dégagements entériques de méthane des bovins de boucherie.** *Can. J. Anim. Sci.* **89**: 409–413. D'importantes émissions de gaz à effet de serre (GES) viennent de l'agriculture; on le doit en grande partie au méthane (CH₄) que libère l'intestin des ruminants. Cette étude examine l'incidence des drèches de distillerie avec solubles (DDS; 30 g de matière grasse par kg de matière sèche alimentaire) sur les émissions entériques de CH₄ quand elles remplacent l'orge (35% de la matière sèche des aliments) dans la ration de semi-finition des bovins de boucherie. L'addition de DDS réduit les émissions de CH₄ (g par jour) de 19,9%, soit 16,4% après ajustement selon l'ingestion de matière sèche (par g de matière sèche ingérée) ou de 23,9% après ajustement en fonction de l'ingestion d'énergie brute (% de l'énergie brute ingérée). Ajouter des DDS à la ration des animaux diminue les émissions de CH₄, mais pour en évaluer totalement l'impact sur l'environnement, il faudrait tenir compte de la teneur en N plus élevée du fumier sur les émissions d'oxyde nitreux et d'ammoniac.

Mots clés: Méthane, bovins de boucherie, drèches sèches de distillerie de maïs avec solubles, lipides, émissions de gaz à effet de serre, hexafluorure de soufre

There is growing social interest in understanding the link between agriculture and environmental stresses like climate change, and how this stress may be exacerbated by an increase in food production to meet the needs of a growing population. As an example, recent attention has focused on the impact of raising livestock on the environment (Food and Agriculture Organization 2006). An evaluation of the true impact of livestock on the environment needs additional research to address key issues, including basic information on the variability in greenhouse gases (GHG) generated by livestock fed a range of diets. It is recognized that the production of enteric methane (CH₄) by ruminants is an important source of GHG because it accounts for 15% of all global CH₄ emissions (Lassef 1997). On a farm scale, enteric

CH₄ emissions accounted for 61% of the total GHG generated from a Japanese beef cow-calf system (Ogino et al. 2007). In general, CH₄ emissions are dependent on the amount of feed consumed and the composition and quality of the diet fed (Johnson and Johnson 1995).

The cattle industry regularly adjusts cattle diets to account for the availability and cost of feed ingredients and by-products, and it is necessary for research to keep pace by measuring the impact of any major changes in feed composition on enteric CH₄ emissions. The objective of our study was to evaluate the response in enteric CH₄ production to the recent practice of feeding corn distillers' dried grains with solubles (DDGS) from the ethanol industry. The evaluation was made relative to the previous practice of using barley grain as the main

supplementary energy source in the grower (i.e., back-grounding) diet of feedlot cattle.

The experimental protocol received institutional approval and was conducted in accordance to the guidelines of Canadian Council on Animal Care (1993). The study was conducted at the beef cattle research feedlot located at Agriculture and Agri-Food Canada's Lethbridge Research Centre (lat. 49°38'N; long. 112°48'W; elevation 900 m). The experiment was designed as a completely randomized block (periods) design with two treatments and three replications (three pens per treatment). It was conducted over 15 wk (2008 Jun. 09 to Sep. 22) and consisted of three periods (Periods 1–3), each 5 wk in duration. Sixty Hereford steers (initial body weight of 381 ± 19 kg) were blocked by weight and then randomized into six pens of 10 cattle before each period. The six pens were then paired to form three groups (Groups 1–3). One of the paired pens within the group received a diet without DDGS (Control), and the other pair received a diet containing DDGS.

The diets were composed of [dry matter (DM) basis] 60% barley silage, 5% pelleted supplement, and either 35% barley grain (Control) or 35% DDGS (Table 1). The DDGS was purchased commercially and contained (DM basis) 30.1% crude protein (CP) and 12.7% crude fat (Table 2). Consequently, the CP content of the diet was higher for the DDGS (17.4% of DM) compared with the Control diet (12.2% of DM). As expected, the gross energy (GE) content of the DDGS diet was higher than that of the Control diet (20.4 vs. 18.5 MJ kg⁻¹ DM) because of the higher crude fat content of DDGS (5.1 vs. 2.0% DM). The fat in corn DDGS is typically rich in C18:2 (58 g 100 g⁻¹ of fatty acid; National Research Council 2001).

The Control diet is representative of feedlot (back-grounding) diets typically fed to cattle prior to the widespread availability of DDGS, while the DDGS diet

is representative of current practices due to the extensive availability of DDGS in western Canada. The diets were offered for ad libitum intake every morning at about 1030 as a total mixed ration. The diets were sampled weekly and dried at 55°C to determine DM content, while theorts were removed from each feed bunk weekly, weighed, sampled and dried (55°C). This information was used to calculate mean daily DM intake (DMI) of each pen of cattle. In addition, samples of the diets and the main ingredients were also taken weekly, bulked by period, dried (55°C), and ground through a sieve with 1-mm holes (standard model 4, Arthur Thomas Co., Philadelphia, PA).

The ground samples were analyzed to characterize the composition of the diets and the main ingredients. Gross energy was determined using a bomb calorimeter (model E2k; CAL2k, Johannesburg, South Africa) and then the samples were sent to Cumberland Valley Analytical Services (Maugansville, MD) for further chemical analysis using wet chemistry. Association of Official Analytical Chemists (AOAC 1995) methods were used to determine analytical DM (method 930.15), organic matter (100 – ash; method 942.05), acid detergent fibre (973.18), CP [6.25 × nitrogen (N); method 990.03], and crude fat (method 920.39). Neutral detergent fibre (no sodium sulphite, modified filtration technique) was determined according to Goering and Van Soest (1970).

Cattle were weighed on the first and last day of each period, and these body weights were used to determine average daily gain (ADG). Emission measurements were initiated only after 2 wk of feeding to ensure the rumen was fully adjusted to the diet. The measurements were made for 3 d during the third week (Group 1), fourth week (Group 2) and fifth week (Group 3). This procedure was repeated for each 5-wk period, resulting in a potential total of 540 emission measurements over the study (i.e., 20 cattle × 3 groups × 3 days × 3 periods). There were 20 cattle measured simultaneously (10 cattle per pen).

During the week that emission measurements were made, the cattle were moved from their feedlot pens to two isolated pens (14 × 18 m; separated by 30 m) on Monday morning at approximately 0930. The isolated pens were located 200 m south of the feedlot, and were connected by an alley to the feedlot to allow easy transfer of cattle between the two sites. Before the cattle entered the isolated pens, each animal was fitted with a head halter and sampling canister (yoke type) for use with the sulphur hexafluoride (SF₆) tracer technique (Johnson et al. 1994). Cattle were temporarily removed from the isolated pens on Tuesday morning (end of day 1) and Wednesday morning (end of day 2) between 0930 and 1030 to change the halters and sampling canisters. On Thursday morning (end of day 3 at 0930), cattle were moved back to feedlot pens after the halters and canisters were removed.

The measurement of enteric CH₄ production was accomplished using the SF₆ tracer technique (Johnson

Table 1. Ingredient composition of the experimental diets

Ingredient ^z , % of the dietary DM	Control	DDGS ^y
Barley silage	60	60
Barley grain, steam-rolled	35	–
Corn DDGS ^y	–	35
Barley grain, ground	2.8	3.4
Canola meal	0.5	–
Urea	0.1	–
Limestone	1.25	1.25
Salt	0.15	0.15
Trace mineral and vitamin mix ^x	0.05	0.05
Molasses, dried	0.125	0.125

^zAll ingredients pelleted, excluding barley silage, steam-rolled barley grain, corn DDGS.

^yDDGS, distillers' dried grains with solubles.

^xContained 23.9% of Ca, 0.02% of P, 0.04% of K, 0.03% of Mg (DM basis), 152 001 ppm of Cu, 59 580 ppm of Zn, 22 979 ppm of Mn, 689 ppm of I, 197 ppm of Co, 3055 ppm of Se, 5 067 000 IU of vitamin A, 502 000 IU of vitamin D, and 13 931 IU of vitamin E.

Table 2. Chemical analysis of the experimental diets and major ingredients (mean ± SD)

Item	Experimental diet		Ingredient		
	Control	DDGS ²	Barley silage	Barley grain	DDGS ²
Number of samples	3	3	3	3	3
Dry matter (DM) (%)	46.7 ± 5.0	47.5 ± 4.6	37.0 ± 6.5	85.7 ± 0.8	88.4 ± 0.3
Organic matter (% of DM)	92.6 ± 0.6	91.4 ± 0.4	90.5 ± 1.5	97.2 ± 0.1	94.9 ± 0.2
Crude protein (CP) (% of DM)	12.2 ± 0.6	17.4 ± 0.5	10.8 ± 0.8	13.8 ± 1.4	30.1 ± 0.5
Soluble CP (% of DM)	4.6 ± 0.5	5.3 ± 0.4	6.2 ± 0.9	1.4 ± 0.1	3.5 ± 0.7
ADIN ³ (% of DM)	—	—	1.5 ± 0.2	1.5 ± 0.3	2.8 ± 0.2
Acid detergent fibre (% of DM)	23.6 ± 1.6	24.7 ± 2.2	34.6 ± 2.3	8.1 ± 0.5	12.1 ± 1.2
Neutral detergent fibre (% of DM)	38.5 ± 1.7	42.4 ± 2.6	51.8 ± 2.6	19.6 ± 1.2	29.2 ± 2.4
Crude fat (% of DM)	2.0 ± 0.0	5.1 ± 0.5	2.4 ± 0.2	2.5 ± 0.1	12.7 ± 0.3
Gross energy (MJ kg ⁻¹ of DM)	18.5 ± 0.2	20.4 ± 0.3	—	—	—

²DDGS, corn distillers' dried grains with solubles.

³ADIN, acid detergent insoluble nitrogen.

et al. 1994) where SF₆ mimics the loss of CH₄ between the rumen and the atmosphere. A small permeation tube containing on average (mean ± SD) 2315 ± 121 mg of ultra pure SF₆ was placed in the rumen 1 wk prior to the start of the trial. A Teflon™ membrane controlled the release of SF₆ gas from the permeation tube. The SF₆ release rates of the 60 permeation tubes used in our study were determined over 3 mo (March to May 2008) prior to this study by weighing the tubes weekly and storing them at 39°C. The release rates ranged from 2.80 to 6.04 mg SF₆ d⁻¹ with an average value of 3.93 ± 0.76 mg SF₆ d⁻¹.

The SF₆ tracer technique captures the respired and eructated air around the nostrils of an animal by drawing it through tubing into an evacuated canister (yoke-like) located on the neck of the animal. The air flow into the canister was restricted using an in-line capillary tube such that the vacuum in the canister was reduced by about 50% over 24 h. The canisters were made from a polyvinyl chloride tube. After removing the canister each morning from the animal, they were pressurized to approximately 103 kPa above ambient pressure. One hour after pressurizing, four 20-mL air samples were removed from each canister sequentially using a syringe and a septum located on the canister, and the four syringe samples were injected immediately into four corresponding Labco Exetainers (6.8 mL; Buckinghamshire, United Kingdom). The air sample in the exetainer was analyzed for the CH₄ and SF₆ mixing ratio within 3 d of sampling using gas chromatography [model HP 5890 fitted with an electron capture detector (ECD) for SF₆ and a flame ionizing detector (FID) for CH₄]. Standard curves for the gas chromatograph were generated throughout the study using five gas standards between 18.27 and 299.50 nmol mol⁻¹ for SF₆, and between 1.57 and 250 μmol mol⁻¹ for CH₄. The correlation coefficient exceeded 99.9% for all standard curves.

The SF₆ and CH₄ mixing ratio (μmol mol⁻¹) in the canisters (C_{sf6} and C_{ch4}, respectively), and the pre-determined SF₆ release rate (Q_{sf6}; g d⁻¹) were used to determine the CH₄ emission (Q_{ch4}; g d⁻¹) using Eq. 1. Background SF₆ and CH₄ mixing ratios (CB_{sf6} and CB_{ch4}, respectively) were measured upwind of the isolated pens using another canister and these were subtracted from C_{sf6} and C_{ch4}, respectively. The ratio of molecular weights (MW) was used to account for the difference in density between the gases.

$$Q_{ch4} = \frac{C_{ch4} - CB_{ch4}}{C_{sf6} - CB_{sf6}} Q_{sf6} \frac{MW_{ch4}}{MW_{sf6}} \quad (1)$$

Mean daily emissions (g CH₄ d⁻¹) and the emissions adjusted for DMI [g CH₄ (kg DMI)⁻¹] and GE intake [MJ CH₄ (MJ GE intake)⁻¹ × 100 or % of GE intake] were calculated for each pen for each period using the feed intakes measured while the cattle were in the isolated pens. When the cattle were in the isolated pens, mean pen DMI was measured daily by removing, weighing, and drying (55°C) theorts daily. Gain to feed ratio for each period was calculated for each pen of cattle by dividing total weight gain by the total DM consumed (main feedlot pens + isolated pens) during the period. All data were analyzed by considering the pen to be the experimental unit.

A mixed model (SAS Institute, Inc. 2005) was used where the fixed variables were period (1–3), day (1–3, CH₄ measurements only) and treatment (Control and DDGS). There was also a random effect specified as treatment × period × group, and day (1–3) was used as a repeated variable (CH₄ measurements only). Release rate of the permeation tube was also included in the original model as a covariate for CH₄ emissions, but was later dropped from the model because it was not significant. Significant differences were declared at *P* < 0.05.

Over the study, 40 of the 540 canisters used in measuring CH₄ emissions (SF₆ tracer technique) were

not used because of either inadequate flow during sampling (intake blockage) or canister damage that caused a loss of vacuum in the canister. The results in Table 3 show a 19% lower CH₄ emission ($P < 0.01$) for cattle fed DDGS (177 g CH₄ d⁻¹) compared with the Control (221 g CH₄ d⁻¹). There was also an effect of period ($P = 0.01$) on CH₄ emissions, where the CH₄ emissions increased from 179 to 220 g CH₄ d⁻¹ over the three periods. The sequential increase in emissions each period coincided with an increase ($P = 0.01$) in DMI. It follows that as the cattle grew, DMI increased as did the CH₄ emission. The effect of period was not surprising, given that it is well established that CH₄ emissions are proportional to DMI (Grainger et al. 2007). There was no impact of group or day on CH₄ emissions.

After adjusting CH₄ emissions for DMI (Table 3), there was a 16.4% ($P = 0.05$) reduction in CH₄ emission for the DDGS diet compared with the Control diet [19.9 vs. 23.8 g (kg DMI)⁻¹]. The DMI-adjusted emissions increased ($P < 0.001$) over the 3 d from 20.5 to 21.8 to 23.1 g (kg DMI)⁻¹, respectively, which coincided with a reduction ($P < 0.001$) in DMI over the 3 d (9.6, 9.2 and 9.0 kg, respectively). The average DMI declined by about 0.35 kg d⁻¹, while the cattle were in the isolated pens, which may indicate that the cattle were stressed by the combined effects of the change in pen location (i.e., from the feedlot to the isolated pens), daily handling and wearing a halter and yoke. A reduction in DMI coinciding with measuring enteric CH₄ using the SF₆ tracer technique was also reported by Hegarty et al. (2007). There was no effect of period on the DMI-adjusted CH₄ emissions, indicating that the increase in CH₄ emissions over the periods was directly related to the increase in DMI that coincided with animal growth. However, there were interactions for treatment × day ($P < 0.001$) and period × day ($P = 0.03$) for DMI-adjusted CH₄ emissions. Methane emissions, as a percentage of GE intake, were also lower ($P < 0.01$) for DDGS

(5.4%) compared with the Control (7.1%), representing a 23.9% decline. Similar to Grainger et al. (2007), we found no significant affect of release rate of SF₆ from the permeation tubes on CH₄ emissions, even though Vlaming et al. (2007) reported that permeation release rate of SF₆ may affect estimates of CH₄ yield.

We attribute the lower CH₄ emission of cattle fed DDGS to the high lipid content of DDGS (12.7% of DM), which, when added to the diet, increased the crude fat content from 2.0 to 5.1% of DM. It is possible that the reduction in CH₄ emission was due to other changes in diet composition with added DDGS, such as increased neutral detergent fibre content and lowered starch content. However, that possibility is unlikely given that CH₄ emissions usually increase, rather than decrease, proportionally with dietary fibre content (Boadi et al. 2004).

Supplementation of diets with lipids that are not protected from ruminal digestion is one strategy recognized to lower enteric CH₄ emissions (Boadi et al. 2004). The observed CH₄ reduction [g (kg DM)⁻¹] of 5.5% per percentage unit of added fat corresponds well with the results of a meta-analysis conducted by Beauchemin et al. (2008). That analysis included a broad range of experimental conditions including different fat sources, levels of added fat, animal species, level of intake, and diet composition, and reported a 5.6% reduction in CH₄ [g (kg DM)⁻¹] with each percentage unit of added fat. Added fats decrease CH₄ emissions by lowering the quantity of organic matter fermented in the rumen, and by exerting toxic effects on cellulolytic bacteria, the activity of ruminal methanogens and protozoal numbers, and for lipids rich in unsaturated fatty acids, through the biohydrogenation process (Johnson and Johnson 1995; Beauchemin et al. 2008). Although our findings were consistent over the 15-wk study, the longer term impact of DDGS needs to be measured to

Table 3. Performance of feedlot cattle fed a backgrounding diet without (Control) or with corn distillers' dried grains with solubles (DDGS)

Variable	Treatment			P-value		
	Control	DDGS	SEM	Trt	Period	Trt × Period
Isolated pens,						
DMI ^a (kg d ⁻¹)	9.5	9.0	0.38	0.42	0.01	0.78
CH ₄ (g d ⁻¹)	221	177	6.2	<0.01	0.01	0.96
CH ₄ ^b (g kg ⁻¹ of DMI)	23.8	19.9	1.26	0.05	0.81	0.88
CH ₄ (% of GE intake)	7.1	5.4	0.37	<0.01	0.71	0.87
Feedlot pens						
DMI (kg d ⁻¹)	10.3	9.9	0.12	0.02	<0.01	0.06
Initial BW (kg)	441	440	2.2	0.81	<0.01	0.98
Final BW (kg)	488	489	2.3	0.76	<0.01	0.09
Change of BW (kg)	47	49	1.3	0.35	0.17	<0.01
ADG (kg d ⁻¹)	1.33	1.44	0.04	0.10	0.30	0.11
Gain:feed	0.13	0.15	0.004	<0.01	<0.01	0.03

^aDay effect: $P < 0.01$.

^bDay effect, treatment × day effect, and period × day effect: $P < 0.05$.

determine whether adaptation of the rumen environment occurs.

There was a trend for higher ADG for cattle fed DDGS compared with the Control (1.44 vs. 1.33 kg d⁻¹; $P = 0.10$). Gain to feed ratio was also higher for cattle fed DDGS compared with Control (0.15 vs. 0.13; $P < 0.01$). However, it must be recognized that our study was not designed (i.e., use of short periods) to examine the effects of DDGS on the performance of feedlot cattle over an entire production cycle. However, our results do support the findings of a recent meta-analysis of Klopfenstein et al. (2008) in which improved animal performance of feedlot cattle fed corn DDGS was reported. In their analysis, a maximum ADG (1.68 kg d⁻¹ vs. a Control finishing diet of 1.50 kg d⁻¹) and gain:feed (0.177 vs. a Control finishing diet of 0.162) were found at 20–30% and 10–20% DDGS, respectively.

Our study shows that the current practice of using DDGS in the diet of growing beef cattle reduces enteric CH₄ production by about 16.4% when adjusted for DM intake, and therefore use of DDGS in cattle diets can be considered a useful CH₄ abatement strategy. However, one limitation to using DDGS as an energy source is that it contributes a substantial amount of CP to the diet. If the CP content of the diet exceeds the animal's requirement, the animal will excrete more N. Higher N excretion of cattle fed diets containing high levels of CP generates higher ammonia (NH₃) emissions (Todd et al. 2006). In general, losses of N as NH₃ emissions from open feedlots are very high, particularly during the summer months (Todd et al. 2006). Farran et al. (2006) reported that about 80% of N excretion was volatilized from the feedlot pen surface. Atmospheric NH₃ is a precursor to the formation of atmospheric aerosols that are linked to human health problems (Popendorf et al. 1985). An additional concern is the deposition of NH₃ to land that can increase the release of nitrous oxide (Loubet et al. 2006).

Adding DDGS to the diet of growing beef cattle substantially reduces enteric CH₄ production, but it is not known whether feeding DDGS is an environmentally sustainable practice for the beef cattle industry. Of particular concern is a possible increase in N cycling and its impact on NH₃ and nitrous oxide emissions. To arrive at a definitive conclusion on the advantages of feeding corn DDGS in feedlot cattle diets, research using a life cycle assessment approach is necessary to determine the impact of DDGS diet on the NH₃ and net GHG budgets.

Association of Official Analytical Chemists. 1995. Official methods of analysis. 16th ed. AOAC, Arlington, VA.

Beauchemin, K. A., Kreuzer, M., O'Mara, F. and McAllister, T. A. 2008. Nutritional management for enteric methane abatement: a review. *Aust. J. Exp. Agric.* **48**: 21–27.

Boadi, D., Benchaar, C., Chiquette, J. and Massé, D. 2004. Mitigation strategies to reduce enteric methane emissions from dairy cows: Update review. *Can. J. Anim. Sci.* **84**: 319–335.

Canadian Council on Animal Care. 1993. Guide to the care and use of experimental animals. Vol. 1. 2nd ed. E. D. Olfert, B. M. Cross, and A. A. McWilliam, ed. CCAC, Ottawa, ON.

Food and Agriculture Organization. 2006. Livestock's long shadow: environmental issues and options. FAO, Rome, Italy.

Farran, T. B., Erickson, G. E., Klopfenstein, T. J., Macken, C. N. and Lindquist, R. U. 2006. Wet corn gluten feed and alfalfa hay levels in dry-rolled corn finishing diets: Effects on finishing performance and feedlot nitrogen mass balance. *J. Anim. Sci.* **84**: 1205–1214.

Goering, H. K. and Van Soest, P. J. 1970. Forage fiber analysis (apparatus, reagents, procedures and some applications). *In* Agriculture handbook no. 379. Agriculture Research Service, United States Department of Agriculture, Washington, DC.

Grainger, C., Clarke, T., McGinn, S. M., Auldist, M. J., Beauchemin, K. A., Hannah, M. C., Waghorn, G. C., Clark, H. and Eckard, R. J. 2007. Methane emissions from dairy cows measured using the sulfur hexafluoride (SF₆) tracer and chamber techniques. *J. Dairy Sci.* **90**: 2755–2766.

Hegarty, R. S., Goopy, J. P., Herd, R. M. and McCorkell, B. 2007. Cattle selected for lower residual feed intake have reduced daily methane production. *J. Anim. Sci.* **85**: 1479–1486.

Johnson, K. A., Huyler, M., Westberg, H., Lamb, B. and Zimmerman, P. 1994. Measurement of methane emissions from ruminant livestock using a sulphur hexafluoride tracer technique. *Environ. Sci. Technol.* **28**: 359–362.

Johnson, K. A. and Johnson, D. E. 1995. Methane emissions from cattle. *J. Anim. Sci.* **73**: 2483–2492.

Klopfenstein, T. J., Erickson, G. E. and Bremer, V. R. 2008. Use of distillers by-products in the beef cattle feeding industry. *J. Anim. Sci.* **86**: 1223–1231.

Lassey, K. R., Ulyatt, M. J., Martin, R. J., Walker, C. F. and Shelton, I. D. 1997. Methane emissions measured directly from grazing livestock in New Zealand. *Atmos. Environ.* **31**: 2905–2914.

Loubet, B., Asman, W. A. H., Theobald, M., Hertel, O. Tang, S. Y., Robin, P., Hassouna, M., Dammgen, U., Genermont, S., Cellier, P. and Sutton, M. A. 2006. Ammonia deposition near hot spots: Processes, models and monitoring methods. Background Document for Working Group 3: UNECE Expert Workshop on Ammonia, Edinburgh, UK. 2006 Dec. 04–06.

National Research Council. 2001. Nutrient requirements of dairy cattle. 7th rev. ed. National Academy of Sciences, Washington, DC.

Ogino, A., Orito, H., Shimada, K. and Hirooka, H. 2007. Evaluating environmental impacts of the Japanese beef cow-calf system by the life cycle assessment method. *Anim. Sci. J.* **78**: 424–432.

Popendorf, W., Donham, K. J., Easton, D. N. and Silk, J. 1985. A synopsis of agricultural respiratory hazards. *Am. Indust. Hygiene Assoc. J.* **46**: 154–161.

SAS Institute, Inc. 2005. SAS OnlineDoc[®] 9.1.3 SAS Institute, Inc., Cary, NC.

Todd, R. W., Cole, N. A. and Clark, R. N. 2006. Reducing crude protein in beef cattle diet reduces ammonia emissions from artificial feedyard surfaces. *J. Environ. Qual.* **35**: 404–411.

Flaming, J. B., Brookes, I. M., Hoskin, S. O., Pinares-Patiño, C. S. and Clark, H. 2007. The possible influence of intreruminal sulphur hexafluoride release rates on calculated methane emissions from cattle. *Can. J. Anim. Sci.* **87**: 269–275.